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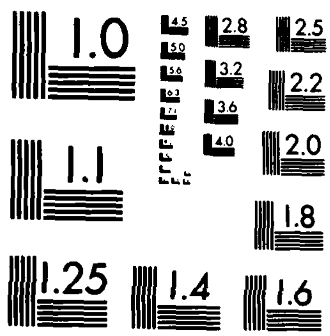

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DEPARTMENT OF DEFENCE SUPPORT

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AERONAUTICAL RESEARCH LABORATORIES

MELBOURNE, VICTORIA

AERODYNAMICS NOTE 414

PRELIMINARY KINEMATIC CONSISTENCY CHECKING OF HELICOPTER FLIGHT DATA

by

N. E. GILBERT and M. J. WILLIAMS

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SUMMARY

A simplified approach to kinematic consistency checking applied to ARL Sea King helicopter flight trials data is given. Prompt implementation of the method has been possible, pending longer term development of systems identification techniques suitable for application in a general way to helicopter data. This has allowed the formation of a trials data bank with reasonable confidence in the kinematic quantities so that validation of the ARL Sea King mathematical model can continue. In the process adopted, measurements are first digitally filtered to remove noise. Alternative values of kinematic quantities are then derived from the smoothed measurements, using numerical differentiation or integration. For quantities obtained by integration, two separate iteration cycles are used, thus enabling kinematic equations to be integrated independently by "separation of variables" using the trapezoidal formula. Uncertainties in some calibration constants are resolved using differences between measured and derived kinematic quantities. A procedure for the replacement of suspect angular measurements by derived values in the calculation of other dependent quantities is described and demonstrated.

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NOMENCLATURE*

X	Uncalibrated signal output (integer in range 0 to 4095)
Y	Generalised kinematic quantity
a_{long}, a_{lat}, a_{norm}	Longitudinal, lateral, and normal accelerations given by accelerometers (include gravitational effect)
a_x, a_y, a_z	Inertial acceleration components in body axes
c, d	Corrected calibration factor and offset
c', d'	Initial estimate of calibration factor and offset
g	Gravitational acceleration
h	Height (altitude)
h_b	Altitude from boom probe static pressure
h_{rad}	Altitude from radio altimeter
k_1, k_2	Gradient and intercept of "best fit" straight line through cross plot time history
p, q, r	Angular velocity components in body axes (roll, pitch, and yaw)
t	Time
u, v, w	Linear velocity components in body axes
u', v', w'	Linear velocity components in vehicle-carried vertical axes
xyz	Body (helicopter fuselage) axes
$x'y'z'$	Vehicle-carried vertical axes
$x_E y_E z_E$	Earth (inertial) axes
x, y, z	Displacement coordinates of linear accelerometers in body axes
ψ, θ, ϕ	Yaw, pitch, and roll Euler angles when rotating earth axes to body axes
ψ', ϕ'	Yaw attitude (compass heading) and roll attitude (w.r.t. vertical z_E axis)

Subscripts

D	Quantity obtained by numerical differentiation
I	Quantity obtained by numerical integration
O	Initial value

* Kinematic quantities are in respect of the helicopter centre of gravity and symbols listed in Tables 1 and 2 are excluded if not referenced in the text.

1. INTRODUCTION

In 1979 the Aeronautical Research Laboratories (ARL) conducted flight trials on a Royal Australian Navy Sea King Mk. 50 helicopter.[1] The primary aim of the trials was to record data which could be used to validate a mathematical model developed by ARL.[2,3] The data acquisition system installed allowed 32 channels of data to be recorded on magnetic tape in serial digital form at a maximum sampling frequency of 60 Hz for any channel.[4] Using a specially built transcriber unit,[5] the data were converted from twin-track to single-track form and stored on computer-compatible seven-track magnetic tape, from which disk files were obtained for each flight record. The process of obtaining disk files and the data reduction procedures used in obtaining fully processed data are given in Reference 6. The procedures allow various corrections and calibrations to be applied, removal of noise, and calculation of many additional quantities. These additional quantities include alternative values of kinematic quantities derived from measurements by means of numerical differentiation or integration. These numerically derived values are hereafter referred to simply as "derived" values.

The general process of comparing measured and derived quantities is commonly referred to as kinematic consistency (or compatibility) checking. It enables the degree of confidence in the flight data to be assessed, and suitable correction to be made to instrument time lags and calibration constants. Systematic methods of applying the checking process have been implemented at ARL[7,8] and NASA Langley Research Center[9] using either Extended Kalman Filter or Maximum Likelihood techniques. However, present indications are that it is difficult to apply these methods in a general way to a particular kinematics problem.

Further studies are currently in progress on the limitations of the methods and on possible improvements. Meanwhile, it is important for ARL to establish a Sea King trials data bank exhibiting such kinematic consistency that significant deficiencies in the Sea King mathematical model may be identified by graphical comparison. Therefore, a simplified approach to kinematic consistency checking has been adopted and the application of the process to the ARL Sea King flight trials forms the basis of this document. Provided adequate improvements to the above systems identification techniques are forthcoming, it may be desirable at a later stage in the validation process to replace the present method with one of these techniques.

Possible comparisons of kinematic quantities are first outlined in Section 2, with the mathematical formulaton of the quantities given in Section 3. In general, the formulation requires routine axis transformations and numerical differentiation and integration. An iterative method with two separate iteration cycles is used so that the kinematic equations can be integrated independently by "separation of variables" using the trapezoidal formula. In Section 4, the use of selected consistency comparisons to update certain calibration constants is given. Using these revised calibrations, the degree of consistency of the measurements is demonstrated for a case not unduly influential in determining the corrections. The procedure adopted for replacing suspect angular measurements with derived values is given in Section 5. Unless these replacements are made, other dependent quantities calculated will also be in error. An example illustrating the effect of replacement of faulty data recorded for roll rate is included.

2. KINEMATIC QUANTITIES COMPARED

Since reference must be made to the axes system in which the kinematic quantities are specified, these axes systems and their relative orientation are first defined in Figure 1. Euler angles are specified in the conventional way for aircraft by the ordered successive rotations in yaw, pitch, and roll of the aircraft body axes with respect to fixed earth axes. Vehicle-carried vertical axes represent the first rotation.

The quantities directly measured, together with their sampling frequency and analogue filter cut-off frequency, are listed in Table 1. The analogue filters used were all sixth-order Butterworth lowpass filters with cut-off frequencies of 3, 6, and 12 Hz. Corresponding time delays arising from the phase shift (assumed linear) in the filters were estimated to be 12, 6, and 3 sampling intervals of 1/60th second.*

Digital Butterworth lowpass filters may be used in the data reduction procedure, if required, to remove any significant noise remaining.[10,11] This is especially important where numerical differentiation is required in the calculation of additional quantities. Two fifth-order filters were found to be adequate for all filtering requirements. One has a high attenuation of 50 dB at the rotor frequency of 3·5 Hz, giving a cut-off frequency of 1·12 Hz, and removes noise at and above the rotor frequency. It is suitable for variables where the energy is confined to relatively low frequencies. The other filter, which has a cut-off frequency of 4 Hz, is used alternatively where the higher frequency content is significant. The latter is generally only required for normal acceleration when violent manoeuvres occur. For both filters, phase shift is corrected on the assumption that is is proportional to frequency (i.e. constant time delay).

The additional quantities calculated are divided into four groups, which are (1) quantities obtained using pressure measurements from a boom-mounted pitot–static probe, (2) blade angles, (3) Euler angles, and (4) quantities for kinematic consistency checking. Table 2 provides a list of each quantity belonging to the above four groups. Documentation on the calculation of the quantities is given in Reference 1 for the first two groups, and in Section 3 of this document for the last two groups.

The kinematic quantities given in groups 1 and 3 of Table 2 are obtained directly from measured values listed in Table 1, and are treated as if measured directly when being compared with derived values listed in group 4 of Table 2. These latter quantities are all obtained by numerical differentiation or integration of measured values and are represented by symbols with subscript "D" or "I" respectively.

Of the derived kinematic quantities, all except vertical velocity w'_I and horizontal velocity magnitude V'_I may be compared with measured quantities. However, consistency comparisons of each of these quantities are implied when comparing measured and derived values of height and horizontal velocity components respectively. A summary of the possible comparisons is given in Table 3. Angular velocities may be compared using components that are expressed either in body axes or as Euler angle derivatives. Although consistency comparisons for angular displacements are implied by those for angular velocities, and vice versa, both types of comparisons were found useful for updating calibration constants (see Section 4).

* In the case of Doppler velocity measurements, a further 0·55 s adjustment was made to correct for an apparent delay in the Doppler smoothing circuit.

TABLE 1

Quantities Measured by Data Acquisition System

Channel number	Quantity measured	Symbol	Sampling frequency (Hz)	Analogue filter cut-off frequency (Hz)
1	Cyclic stick position—pitch	θ_{stk}	60	12
2	Cyclic stick position—roll	ϕ_{stk}	60	12
3	Collective stick position	θ_{Cstk}	60	12
4	Angle of attack	α	60	12
5	Fore–aft (pitch) push–pull rod position	d_{auxp}	60	3†
6	Lateral (roll) push–pull rod position	d_{auxr}	60	12
7	Collective (altitude) push–pull rod position	d_{auxa}	60	12
8	Pitch rate	q	60	12
9	Sideslip angle	β	60	12
10	Roll attitude	ϕ'	60	12
11	Roll rate	p	60	12
12	Longitudinal acceleration	a_{long}	60	12
13	Lateral acceleration	a_{lat}	60	12
14	Normal acceleration	a_{norm}	60	12
15	Pitch attitude (Euler angle)	θ	30	6
16	Yaw pedal position	d_{ped}	30	6
17	Yaw rate	r	30	6
18*	Yaw attitude (heading)	ψ'	30	—
19	Lateral cable angle	ϕ_{cH}	30	6
20	Longitudinal cable angle	θ_{cH}	30	6
21	Doppler longitudinal velocity	u'	15	6
22	Doppler lateral velocity	v'	15	6
23	Boom probe dynamic pressure	q_b	15	12
24	Radio altitude (raw)	h_{rad}	15	3
25	Radio altitude (smooth)	h_{rad}	15	3
26	Boom probe absolute pressure	p_b	15	3
27	Yaw push–pull rod position	d_{auxy}	15	12†
28	Ambient temperature	T_{amb}	15	—
29	Torque—Engine 1	Q_1	15	—
30	Rotor r.p.m.	N_R	15	—
31	Towed probe dynamic pressure	q_t	15	3
32	Boom probe—towed probe differential pressure	Δp	15	3
33	Clock time—in octal (5 least signif. digits)	t_{clock}	60	—

* Switch selectable alternative measurement of "Torque—Engine 2" (Q_2).

† Filters inadvertently interchanged.

Notes:
1. Push–pull rod positions represent auxiliary servo displacements.
2. Acceleration measurements include gravitational effects.
3. Pitch and roll attitude are relative to the vertical (hence roll attitude is not an Euler angle).
4. Linear accelerations and angular velocities are in body axes.
5. Doppler velocities are in vehicle-carried vertical axes.
6. Cable angles are measured with respect to the funnel axis of symmetry.
7. Channel numbers represent order of sampling and are also used as identifiers in data processing.

TABLE 2

Additional Quantities Calculated

Channel number	Quantity calculated	Symbol	Group
34	Airspeed from boom probe at standard sea level conditions, corrected for position error	V_C	1
35	Altimeter setting	QNH	1
36	Sea level temperature	T_o	1
37	Altitude from boom probe static pressure	h_b	1
38	True airspeed at aircraft altitude	V_A	1
39	Wind velocity	V_W	1
40	Direction from which wind is coming	ψ_W	1
41	Longitudinal cyclic blade pitch angle	B_{1s}	2
42	Lateral cyclic blade pitch angle	A_{1s}	2
43	Collective blade pitch angle	θ_C	2
44	Tail rotor collective blade pitch angle	θ_T	2
45	Collective blade pitch angle at 75% rotor radius position	θ_{C75}	2
46	Yaw Euler angle	ψ	3
47	Roll Euler angle	ϕ	3
48	Yaw Euler angle derivative—by differentiation	$\dot{\psi}_D$	4
49	Pitch Euler angle derivative—by differentiation	$\dot{\theta}_D$	4
50	Roll Euler angle derivative—by differentiation	$\dot{\phi}_D$	4
51	Roll rate—by differentiation	p_D	4
52	Pitch rate—by differentiation	q_D	4
53	Yaw rate—by differentiation	r_D	4
54	Longitudinal inertial acceleration	a_x	4
55	Lateral inertial acceleration	a_y	4
56	Normal inertial acceleration	a_z	4
57	Longitudinal velocity derivative	$\dot{u}$	4
58	Lateral velocity derivative	$\dot{v}$	4
59	Normal velocity derivative	$\dot{w}$	4
60	Longitudinal velocity—(in vehicle-carried vertical axes) —by integration	u'_I	4
61	Lateral velocity (in vehicle-carried vertical axes)—by integration	v'_I	4
62	Vertical velocity—by integration	w'_I	4
63	Horizontal velocity magnitude $(u'^2_I + v'^2_I)^{1/2}$	V'_I	4
64	Height—by integration	h_I	4
65	Yaw Euler angle derivative	$\dot{\psi}$	4
66	Pitch Euler angle derivative	$\dot{\theta}$	4
67	Roll Euler angle derivative	$\dot{\phi}$	4
68	Yaw Euler angle—by integration	ψ_I	4
69	Pitch Euler angle—by integration	θ_I	4
70	Roll Euler angle—by integration	ϕ_I	4

Notes: 1. Linear accelerations, linear velocity derivatives, and angular velocities are in body axes, unless otherwise stated.

2. Euler angles are measured with respect to earth axes.

3. Channel numbers are used only for identification in data processing.

TABLE 3

Summary of Comparisons of Kinematic Quantities

Quantity	Measured*		Derived†	
	Symbol	Channel No.	Symbol	Channel No.
Angular displacements (Euler angles)	ψ	46	ψ_I	68
	θ	15	θ_I	69
	ϕ	47	ϕ_I	70
Angular velocities (in body axes)	p	11	p_D	51
	q	8	q_D	52
	r	17	r_D	53
Angular velocities (Euler angle derivatives)	$\dot{\psi}$	65	$\dot{\psi}_D$	48
	$\dot{\theta}$	66	$\dot{\theta}_D$	49
	$\dot{\phi}$	67	$\dot{\phi}_D$	50
Horizontal linear velocities (in vehicle-carried vertical axes)	u'	21	u'_I	60
	v'	22	v'_I	61
Height‡	h_{rad}	24	h_I	64
	h_b	37		

* In some cases, axis transformation of measured values are required.

† In all cases, numerical differentiation (subscript D) or integration (subscript I) of measured values is required.

‡ For measured height, h_{rad} is used up to 500 ft altitude; otherwise h_b is used.

3. MATHEMATICAL FORMULATION OF KINEMATIC QUANTITIES

3.1 Measured Quantities

Except for pitch attitude θ, the angles given by the aircraft vertical gyro are not Euler angles. Yaw attitude ψ' is a compass heading and roll attitude ϕ' is measured with respect to the vertical z_E axis rather than the axis obtained after first rotating the z_E axis in the pitch plane by θ (see Fig. 1). For these two angles, conversion to Euler angles is given by

$$\psi = \psi' - \psi'_0 \tag{1}$$

$$\phi = \arctan[\tan \phi' \cos \theta] \tag{2}$$

where ψ'_0 is the initial value of ψ'.

Angular velocities p, q, and r in body axes are given directly by rate gyros aligned with the body axes. These rates may be transformed to Euler angle derivatives $\dot{\phi}$, $\dot{\theta}$, and $\dot{\psi}$ using Equations (9) to (11) below.

Horizontal linear velocity components u' and v' are given directly by the Doppler velocity measuring system of the helicopter. Height h is given by the radio altimeter for altitudes up to 500 ft (i.e. $h = h_{rad}$), and by calculations using static pressure measurements obtained from the boom probe for altitudes above 500 ft (i.e. $h = h_b$).

3.2 Derived Quantities

Each of the alternative values of kinematic quantities are derived by either numerical differentiation, using the backward difference formula, or numerical integration, using the

trapezoidal formula. Adequate digital filtering of measurements allows sufficient accuracy to be achieved when numerically differentiating.

In Table 3, only angular velocities are obtained by differentiation. They are given as Euler angle derivatives by direct numerical differentiation of Euler angles, i.e.

$$\dot{\phi}_{\mathrm{D}} = d\phi/dt \tag{3}$$

$$\dot{\theta}_{\mathrm{D}} = d\theta/dt \tag{4}$$

$$\dot{\psi}_{\mathrm{D}} = d\psi/dt \tag{5}$$

or alternatively, following axes transformation, as angular velocity components expressed in body axes by[12]

$$p_{\mathrm{D}} = \dot{\phi}_{\mathrm{D}} - \dot{\psi}_{\mathrm{D}} \sin\theta \tag{6}$$

$$q_{\mathrm{D}} = \dot{\theta}_{\mathrm{D}} \cos\phi + \dot{\psi}_{\mathrm{D}} \cos\theta \sin\phi \tag{7}$$

$$r_{\mathrm{D}} = -\dot{\theta}_{\mathrm{D}} \sin\phi + \dot{\psi}_{\mathrm{D}} \cos\theta \cos\phi \tag{8}$$

The remaining derived quantities in Table 3 are all obtained by integration of the following kinematic equations.[7,12]

$$\dot{\phi} = p + q \tan\theta \sin\phi + r \tan\theta \cos\phi \tag{9}$$

$$\dot{\theta} = q \cos\phi - r \sin\phi \tag{10}$$

$$\dot{\psi} = (q \sin\phi + r \cos\phi)/\cos\theta \tag{11}$$

$$\dot{u} = a_x - (qw - rv) \tag{12}$$

$$\dot{v} = a_y - (ru - pw) \tag{13}$$

$$\dot{w} = a_z - (pv - qu) \tag{14}$$

$$\dot{h} = u \sin\theta - v \cos\theta \sin\phi - w \cos\theta \cos\phi \tag{15}$$

where u, v, and w are linear velocity components in body axes; and a_x, a_y, and a_z are inertial linear acceleration components in body axes.*

In obtaining the inertial accelerations from accelerometer measurements, allowance must first be made for gravitational acceleration components and offset displacements of the accelerometers from the centre of gravity. The inertial accelerations are given by[12]

$$a_x = a_{\mathrm{long}} - g \sin\theta + (q^2 + r^2)x - (pq - \dot{r})y - (pr + \dot{q})z \tag{16}$$

$$a_y = a_{\mathrm{lat}} + g \cos\theta \sin\phi - (pq + \dot{r})x + (p^2 + r^2)y - (qr - \dot{p})z \tag{17}$$

$$a_z = a_{\mathrm{norm}} + g \cos\theta \cos\phi - (pr - \dot{q})x - (qr + \dot{p})y + (p^2 + q^2)z \tag{18}$$

where g is gravitational acceleration and x, y, and z are linear displacement coordinates of the accelerometers in body axis. If the angular velocity measurements are not filtered or smoothed, the above offset displacement corrections are removed by setting x, y, and z to zero. This is because of large errors in angular accelerations arising from numerical differentiation.

In the system identification methods discussed earlier, Equations (9) to (15) are generally solved as coupled differential equations using, typically, a Runge–Kutta or predictor–corrector numerical method of integration. Provided initial values of the state variables ϕ, θ, ψ, u, v, w, and h are known, only linear acceleration and angular velocity measurements are required for the complete solution.

In the simplified iterative method adopted here, which is represented by a block diagram in Figure 2, the equations are integrated independently by "separation of variables" using the trapezoidal formula for numerical integration. Cross-coupling is accounted for by the use of two separate iterative cycles, one for angular displacements θ and ϕ, and the other for linear velocities u, v, and w. Since ψ and h are not coupled back into the differential equation, i.e. they do not appear on the right-hand side of Equations (9) to (15), they may be obtained, following the iterative cycles, by direct integration of Equations (11) and (15) respectively. In each iterative cycle, the state variables coupled back into the differential equations are assumed given by the

* In Reference 7, a_x, a_y, and a_z are equivalent to a_{long}, a_{lat}, and a_{norm} of this document.

best estimates available. These estimates are the last value calculated, either at the previous iteration or, for the first iteration of each time step, at the previous time step. For each iterative cycle, two iterations (i.e. prediction and correction) were generally required for convergence (defined when successive values are within 10^{-5} rad for angular displacements and 10^{-5} ft/s for linear velocities).

Because calibrations for the attitude gyros could be established more accurately than those for the rate gyros, measurements of angular displacement are used in preference to values given by integration of Equations (9) and (11) when values of θ and ϕ are required on the right-hand side of Equations (15) to (18). However, the data reduction computer program REFINE[6] allows the integrated values to be used instead by the user specifying that the measured angular displacements θ and ϕ are faulty (see Section 5). When this is done, the solution will correspond to that given by the general method of solution as coupled differential equations.

Initial values of the state variables, i.e. ϕ_0, θ_0, ψ_0, u_0, v_0, w_0, and h_0, are obtained from measurements, following any necessary axis transformations and, since vertical velocity is not measured, assuming level flight at the beginning of the flight record (i.e. $w'_0 = -\dot{h}_0 = 0$). Velocity components are transformed from vehicle-carried vertical axes to body axes by

$$u_0 = u'_0 \cos \theta_0 \tag{19}$$

$$v_0 = u_0' \sin \theta_0 \sin \phi_0 + v'_0 \cos \phi_0 \tag{20}$$

$$w_0 = u'_0 \sin \theta_0 \cos \phi_0 - v'_0 \sin \phi_0 \tag{21}$$

Hence, by definition, the derived values coincide with the measured one initially.

In order to compare measured and derived linear velocities, values obtained by integration are transformed from body axes to vehicle-carried vertical axes by

$$u' = u \cos \theta + v \sin \theta \sin \phi + w \sin \theta \cos \phi \tag{22}$$

$$v' = v \cos \phi - w \sin \phi \tag{23}$$

$$w' = -u \sin \theta + v \cos \theta \sin \phi + w \cos \theta \cos \phi \tag{24}$$

Comparing Equations (15) and (24), it can be seen, as one would expect, that $w' = -\dot{h}$.

4. USE OF COMPARISONS TO UPDATE CALIBRATION CONSTANTS

Provided there is reasonable agreement between measured and derived kinematic quantities, any remaining differences are generally attributed to inaccuracies in certain calibration constants. In the systems identification methods, most of these uncertainties are usually resolved simultaneously for a given flight record, taking into account the varying user-defined levels of confidence in the accuracy of the assumed constants. With the simplified approach adopted here for the Sea King trials data, the uncertainties are resolved separately as follows.

In general, one of the quantities in each comparison is sufficiently accurately known for it to be used as a reference. If the measured quantity is used as this reference, then calibration errors may usually be attributed to one variable which makes a dominant contribution to the derived quantity (e.g. q in Equation (10) giving θ_I). Since calibrations for the attitude gyros could be established more accurately than those for the rate gyros, angular displacements are used as a reference, and differences in the compared values of angular quantities are attributed to erros in rate gyro calibrations. For the translational quantities, all calibration constants could be established with comparable accuracy. However, even very small errors in the calibration offsets of the linear accelerometers result in a significant error accumulation when integrated to give velocities. This sensitivity is even more pronounced for normal acceleration when effectively integrated twice to give height. Measured horizontal linear velocities, given by u' and v', and height, given by either h_{rad} or h_b, are therefore used as references, and differences in compared quantities are attributed to errors in linear accelerometer calibration offsets. Results are now presented that demonstrate the way in which the comparisons are used to update calibration factors and offsets for the rate gyros and calibration offsets for the linear accelerometers.

For the rotational quantities, comparisons of angular velocities are first used to obtain corrections for both calibration factors and offsets of rate gyros. Good corrections for calibration

factors are obtained, but, because of sensitivity problems, angular velocity comparisons do not provide as good corrections for the offsets. The latter are obtained more reliably from angular displacement comparisons. For selected flight records where large amplitude signals are recorded, Figure 3‡ shows comparisons between measured and derived angular velocities using the initial calibration estimates of the rate gyros. To obtain the desired calibration corrections, the measured and derived values are cross plotted in Figure 4. Ideally, the cross plotted time histories should coincide with the broken lines shown which have unit gradient and zero intercept. The measured deviation from this line is used to correct both calibration factor and offset as described in Appendix A. Basing corrections on the average over a number of flight records, new comparisons, given in Figures 5 and 6, show most of the earlier differences to have been eliminated.

Quantities derived by integration are very sensitive to small offset errors in the quantities integrated. Hence, comparisons of angular displacements, as well as linear velocities and height, may be used to correct the offset errors in measurements of angular velocities and linear accelerations. As stated earlier, derived values of height are particularly sensitive to offset errors because of the double integration required. In order to minimize cross-coupling effects, steady level flight conditions are desirable. Figures 7 and 8 show comparisons of the above quantities for a flight record with such conditions. A straight-forward correction procedure is then possible in which the correction is given by the accumulated differences divided by the time t for the single integration quantities, and by $\frac{1}{2}t^2$ for the double integration quantity. Again basing corrections on the average over a number of records, further improvement in agreement between comparisons, which are given in Figures 9 and 10, may be observed.

The above procedures and resulting corrections are summarised in Tables 4 and 5. In averaging over most of the flight records analysed for consistency, greater weighting was placed on records likely to result in more accurate corrections; i e. those with large angular rates for rate gyro calibrations when using cross plots, and those with steady level flight (mainly flight number 5) for rate gyro and accelerometer offsets when using the accumulated errors. Because of the sensitivity of results to small shifts in calibration offsets, it has been found necessary to redetermine the calibration offsets for a few specific flights. These are referred to in Table 5 as exceptions.

In order to establish confidence in the updated calibrations, it is important that good consistency be obtained for flight records that are not unduly influential in determining the corrections. In Figures 11 to 13, consistency comparisons of angular velocities, angular displacements, horizontal linear velocities, and height are given for a manoeuvre consisting of a pair of lateral doublets. Consistency is observed to be good for all quantities, except for height, where, as stated previously, there is high sensitivity to the calibration offset of the accelerometer measuring normal acceleration.

TABLE 4

Correction Procedures for Calibration Constants

(*a*) Using Cross Plots

Reference variable	Cross plotted variable—corrected for calibration factor and offset	Correction formulae*
p_D	p	$c = c'/k_1$
q_D	q	$d = (d' - k_2)/k_1$
r_D	r	

* Following correction, $d \rightarrow d'$ before stage (*b*).

‡ On the figures, flight records are identified by a computer file number and, where first specified, by a flight number (1 to 7).

TABLE 4 (continued)

(b) Using Accumulated Errors

Reference variable (Y)	Compared variable (Y_I)	Variable corrected for offset	Correction formula
ψ	ψ_I	r	
θ	θ_I	q	
ϕ	ϕ_I	p	$d = d' + (Y - Y_I)/t$
u'	u'_I	a_{long}	
v'	v'_I	a_{lat}	
h_{rad} or h_b	h'_I	a_{norm}	$d = d' + (Y - Y_I)/(\frac{1}{2}t^2)$

TABLE 5

Corrections to Calibration Constants

Quantity	Channel No.	Type*	Initial estimate	From cross plot	From accumulated error†
p	11	c	−0·02808	−0·0303	—
q	8	c	−0·0171	−0·0150	—
r	17	c	0·0146	0·0164	—
p	11	d	56·6	61·3	61·44
q	8	d	37·3	32·7	32·7
r	17	d	−29·6	−33·0	−33·09
a_{long}	12	d	326·1	—	325·7
a_{lat}	13	d	321·9	—	321·8
a_{norm}	14	d	−322·0	—	−321·85

* c = calibration factor; d = calibration offset.

† Based primarily on Flight 5 with following specified exceptions:
for p, d = 61·24 (Flt 3), =61·37 (Flt 4), =61·08 (Flt 7);
for q, d = 32·8 (Flt 3).

5. REPLACEMENT OF FAULTY MEASURED DATA BY DERIVED DATA

Invalid measurements occur for reasons that include overloading and malfunctioning in the instrument or recording system. The resulting problem is that a number of derived quantities may be significantly affected by cross-coupling effects involving a single inaccurately measured variable. For these derived values to be of any use, either for consistency comparisons or as replacements of faulty measurements, the effects of any such faulty data must be fully accounted for when solving the kinematic equations.

The program REFINE[6] allows the user to specify any suspect measurements of angular velocities and displacements as being faulty. Provided angles θ and ϕ are not too large, there is strong coupling between corresponding angular displacements and velocities, i.e. between ϕ and p, θ and q, and ψ and r. Hence, though REFINE does not restrict the user's choice, meaningful results can only be obtained by assuming that at least one variable in each pair is correctly

given. Faulty measurements of angular velocities are replaced in Equations (9) to (15) by corresponding values obtained by differentiation. When the measured values of angular displacements used in Equations (15) to (18) are faulty, they are replaced by those derived by integration.

An example of the consequence of using faulty data and its subsequent replacement by derived data is illustrated in Figure 14. During flight, the roll rate gyro mounting became loose, causing faulty measurement of roll rate. The helicopter was in nominally trimmed level flight with a constant sideways velocity of 15 ft/s in the starboard direction (i.e. $v' = 15$ ft/s). Multiplication of the correspondingly large value of v by the large erroneous value of p (indicated by comparing with p_D) results in a significant error when integrating Equation (14) to give w. This in turn causes a chain reaction of significant error accumulation in v, w, and h given by the equations, because ever increasing errors are coupled back into the equations. The effect of these error accumulations in v'_I and h_I is shown in Figure 14. Also shown is the effect of using p_D instead of p in the equations, which then results in very good agreement with measured values. The computer terminal messages and user responses obtained when running REFINE with this replacement of faulty data are given in Appendix B.

6. CONCLUDING REMARKS

To identify significant deficiencies in the Sea King mathematical model, it is important to establish reasonable confidence in the flight data by kinematic consistency checking. At present, further work is required before the powerful systems identification techniques can be applied reliably in a general way to helicopter flight data. Meanwhile, in order to obtain promptly a suitable trials data bank, a simplified approach has been adopted. In the method, noise is first removed from the data by digital filtering. Alternative values of kinematic quantities are then derived from the smoothed measurements, using numerical differentiation or integration. An iterative method with two iteration cycles enables the kinematic equations to be integrated independently by "separation of variables" using the trapezoidal formula. Generally, differences between measured and derived kinematic quantities have been attributed solely to inaccuracies in those calibration constants that were the least accurately established. If such calibrations are revised to remove the inconsistencies in certain cases, then it has been shown that good kinematic consistency is achieved in other sets of measurements made with the same instruments. Where invalid angular measurements occur, a procedure for their replacement by numerically derived values in the calculation of other dependent quantities has been described and demonstrated.

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APPENDIX A

Correction of Calibration Constants of Angular Velocities Using Cross Plotted Time Histories

Corrections to calibration factors and offsets of rate gyros may be obtained from cross plotted time histories of measured and derived angular velocities as follows.

For each angular velocity component, represented here in a generalised way by Y, the gradient k_1 and intercept k_2 of a "best fit" straight line hand drawn through the time history is first determined, giving the relationship

$$Y = k_1 Y_D + k_2 \tag{A.1}$$

For a signal output X, the measured quantity Y in the above equation is given by

$$Y = c'X + d' \tag{A.2}$$

where c' and d' are the initial estimates of the calibration factor and offset respectively. If the corrected calibration factor and offset are represented by c and d respectively, the correctly measured value of the quantity is given by $cX+d$. It is assumed that this correct value may be equated to Y_D, since Y_D is obtained principally by differentiating the corresponding angular displacement, which is considered correctly measured. Hence,

$$Y_D = cX + d \tag{A.3}$$

By substituting for Y and Y_D from Equations (A.2) and (A.3) in Equation (A.1), and comparing coefficients, the corrected calibration constants are given by

$$c = c'/k_1 \tag{A.4}$$

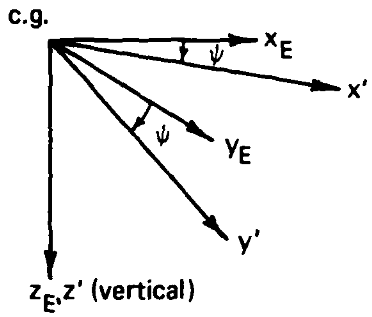
$$d = (d' - k_2)/k_1 \tag{A.5}$$

APPENDIX B

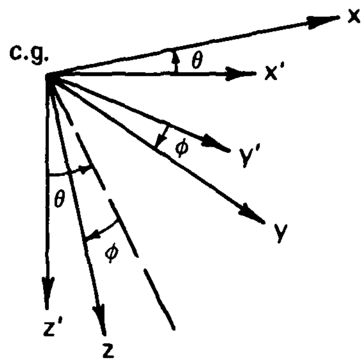
Use of Data Reduction Program REFINE in Replacing Faulty Measured Data by Derived Data

```
.RU REFINE


INPUT DATA FILENAME = 25011
".DAT" OUTPUT FILENAME (w/o ext) = 25011
TITLE (2 lines of 60 chrs)
:25011            TRIMMED FLIGHT - ROLL RATE CORRECTED
:                 AFCS ON - FLT 3 - 30 KM/HR STARBOARD
ARE ASSIGNED BLK NUMBERS REQRD : N
CALIBRATION FILENAME = CAL
FLIGHT NUMBER = 3
DOES CHANNEL 18 MEASURE TORQUE : N
OUTPUT INTERVAL (in 60'ths of sec; e.g. 12 for 0.2 sec) = 6
STARTING TIME DELAY, NO. BLKS FIRST IGNORED = 0,0
TIME LIMIT = 0
IS FILTERING REQRD : Y
IS OUTPUT OF FILTER CHARACTERISTICS REQRD : N
ARE DIGITAL FILTER DELAY ADJUSTMENTS REQRD : Y
IS SMOOTHING REQRD : N
ARE INSTRUMENT & ANALOGUE FILTER DELAY ADJUSTMENTS REQRD : Y
ARE SCALES AND OFFSETS REQRD : Y
ARE PLOT LIMITS REQRD : Y
ARE DROP-OUTS TO BE CORRECTED : Y
ARE ALL CHANNELS REQRD : N
CHANNEL NUMBERS REQRD FOR FOLLOWING GROUPS
[Set first value -ve if excluding]
[Set first value to -100 if none excluded]
  Instumentation data   ( 1 to 33) : 11,22,24
  Boom calculations     (34 to 40) :
  Blade angles          (41 to 45) :
  Euler angles          (46 to 47) :
  Kinematic consistency (48 to 70) : 51,61,64
DATE = 11-May-82
TIME = 09:40
IS KINEMATIC CONSISTENCY ITERATION INFORMATION REQRD : N
ARE ANY FAULTY DATA TO BE REPLACED BY ALTERNATIVELY DERIVED DATA : Y
[Following answer of Y, lower & upper time limits may be typed]
  Angular velocities    -     p : Y
                              q :
                              r :
  Angular displacements -   phi :
                          theta :
                            psi :
No. time corrections =   0
No. blocks replaced =   0
No. drop-out corrections = 658
STOP  000001

END OF EXECUTION
CPU TIME: 1:4.39        ELAPSED TIME: 3:7.24
EXIT
```

Axes $x_E\ y_E\ z_E$ — earth (inertial) axes
$x'\ y'\ z'$ — vehicle-carried vertical axes
$x\ y\ z$ — body (helicopter fuselage) axes



a) Vehicle-carried vertical axes relative to earth axes (earth axes translated such that origin is at c.g.)

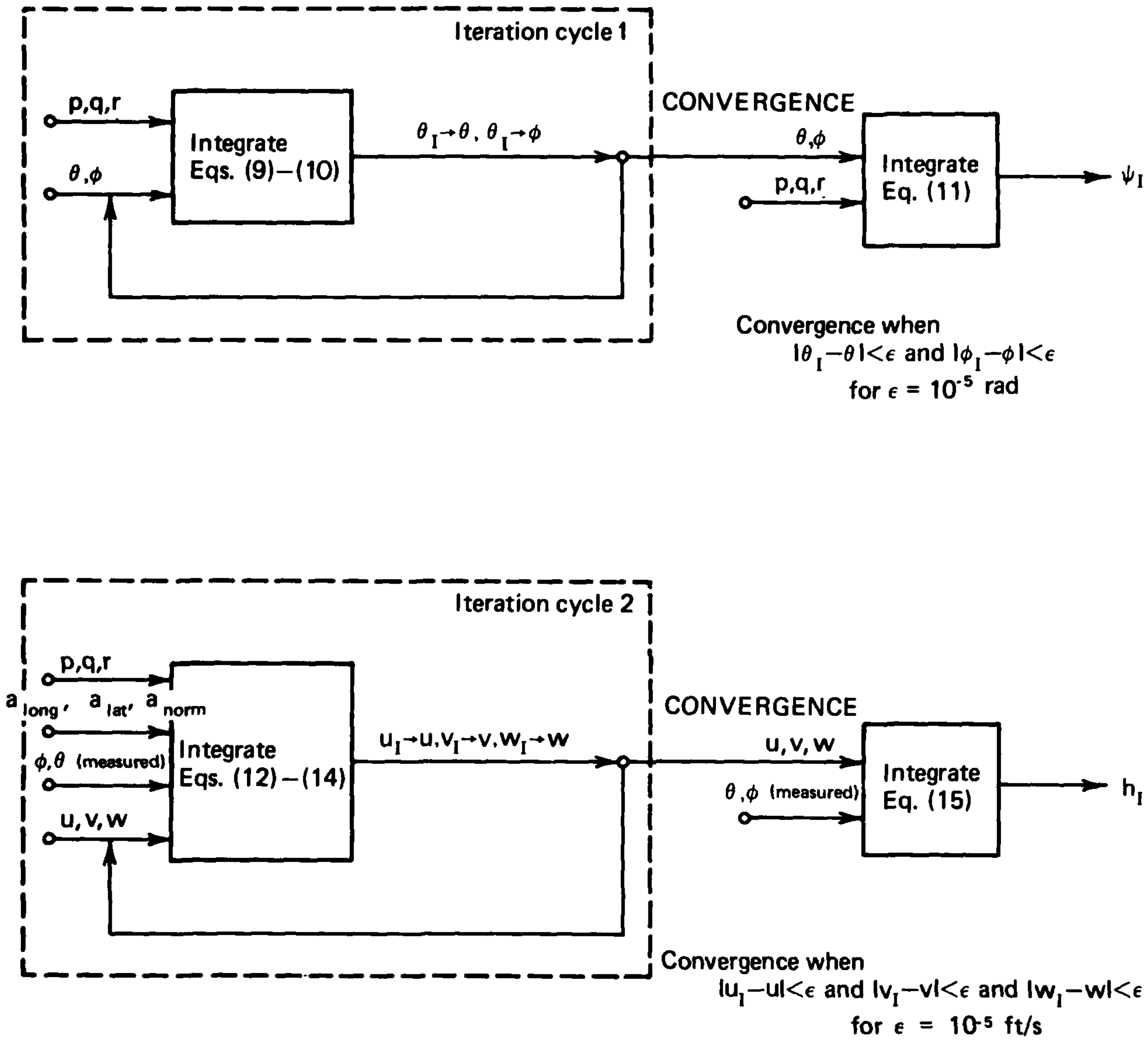


b) Body axes relative to vehicle-carried vertical axes

Notes:

1. All axes systems are right-handed orthogonal.
2. Horizontal x' axis always lies in fuselage longitudinal plane of symmetry (positive forward).
3. Vehicle-carried vertical axes coincide with earth axes at initial time.
4. Orientation of body axes relative to earth axes are defined in conventional way for aircraft, i.e. successive rotations in yaw ψ, pitch θ, and roll ϕ. Vehicle-carried vertical axes represent first intermediate stage, i.e. rotation in yaw ψ.

Fig. 1 Definition of axes systems and their relative orientation



Note: Eq. (14) first gives $w_I \rightarrow w$, which is then used in Eqs. (12) and (13)

Fig. 2 Block diagram showing iterative method of solution of kinematic equations

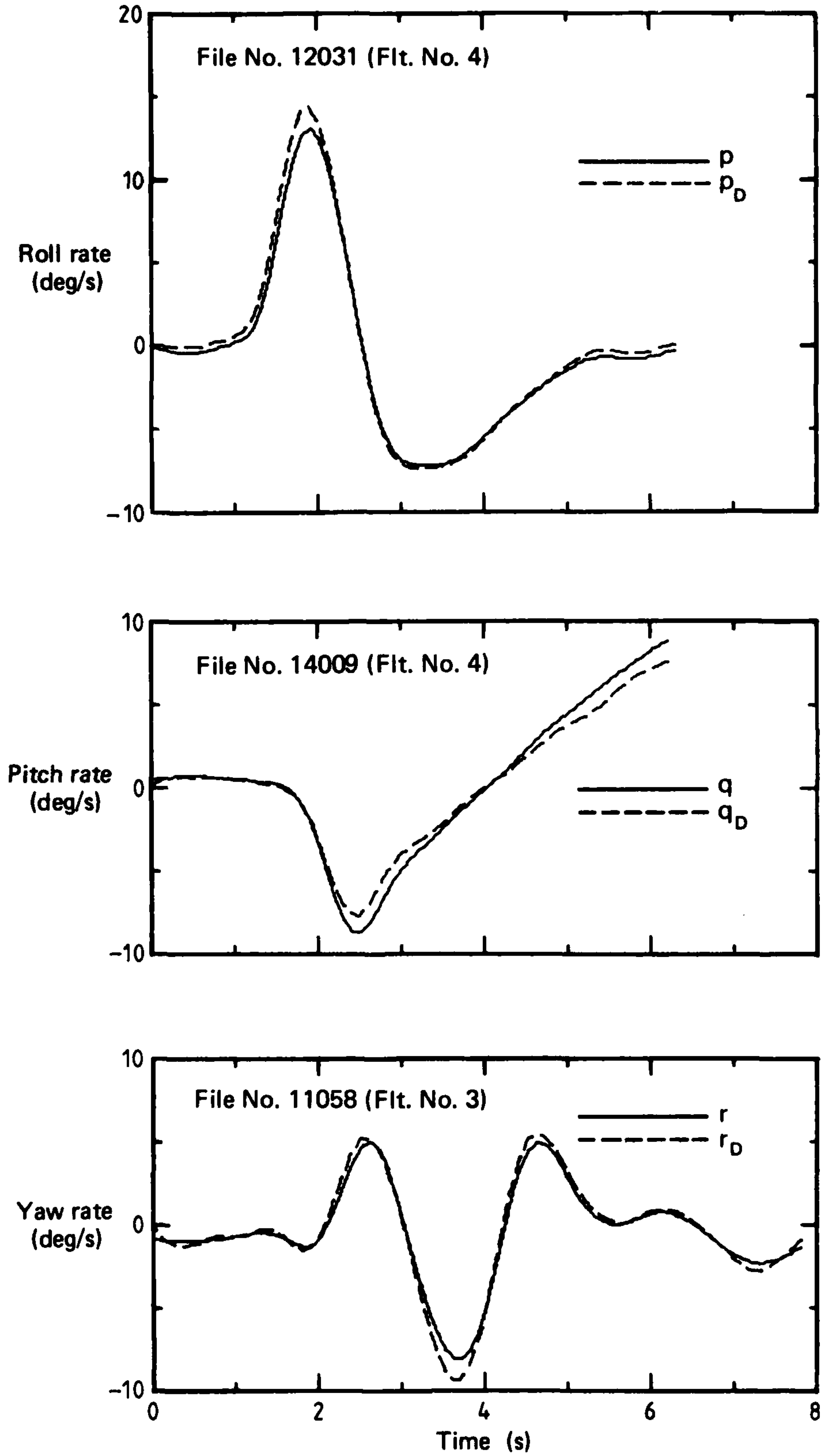


Fig. 3 Comparison between measured values of angular velocities and values derived by differentiation of angular displacements using initial calibration estimates of rate gyros

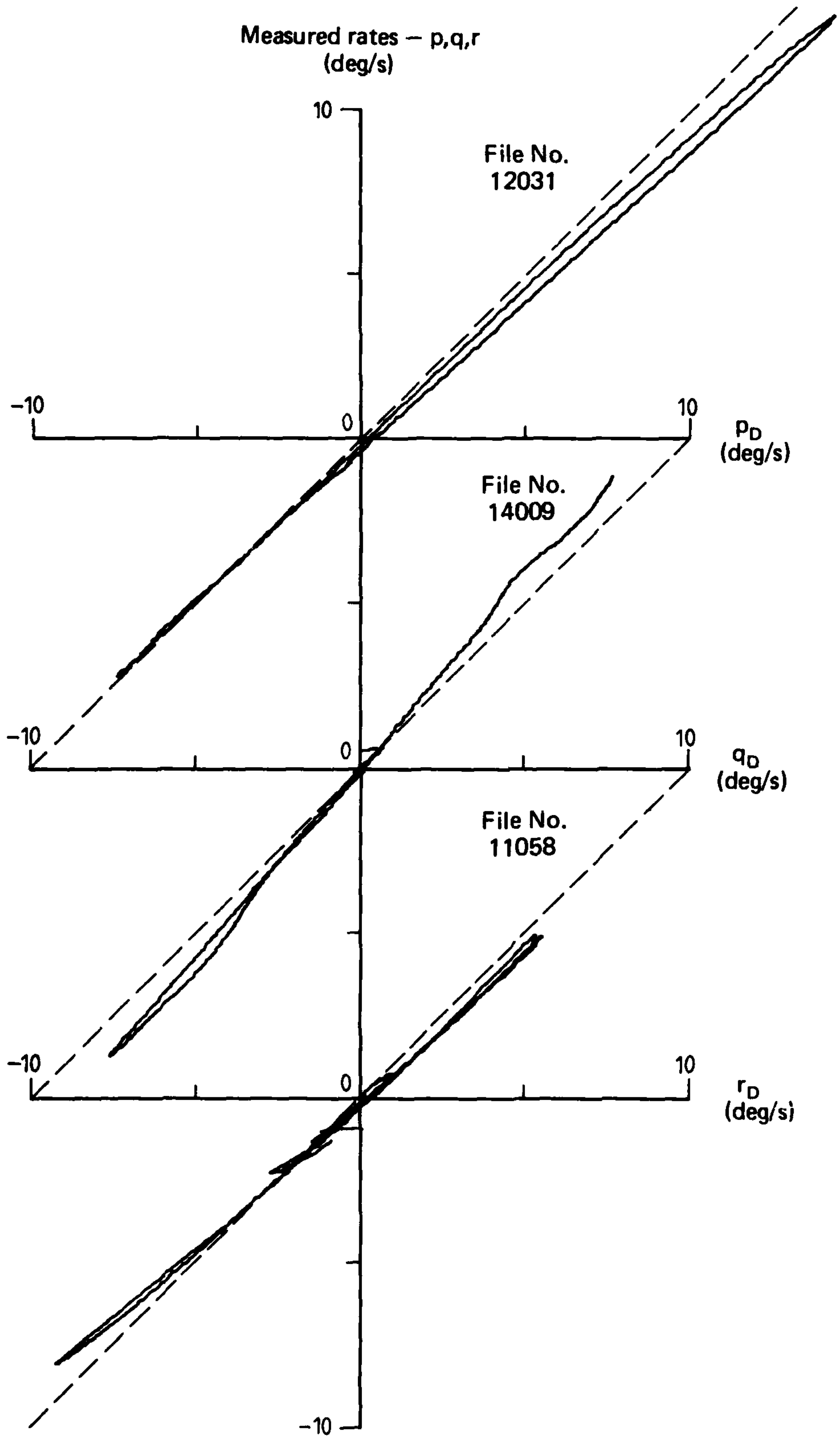


Fig. 4 Cross plots of measured vs. derived values of angular velocities corresponding to results shown in Fig. 3

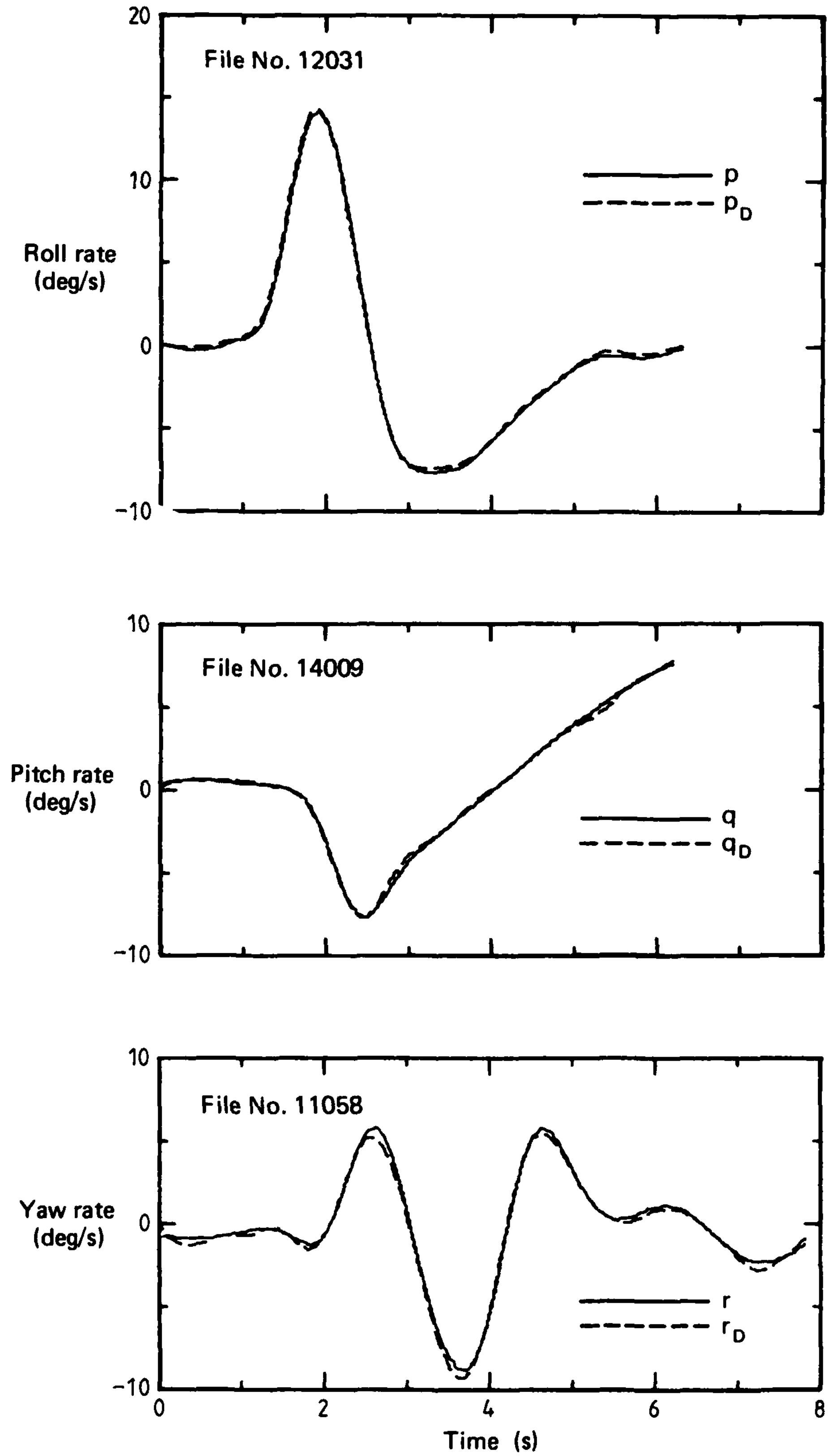


Fig. 5 As Fig. 3, but with calibrations obtained by averaging results derived from cross plot data for a number of flight records

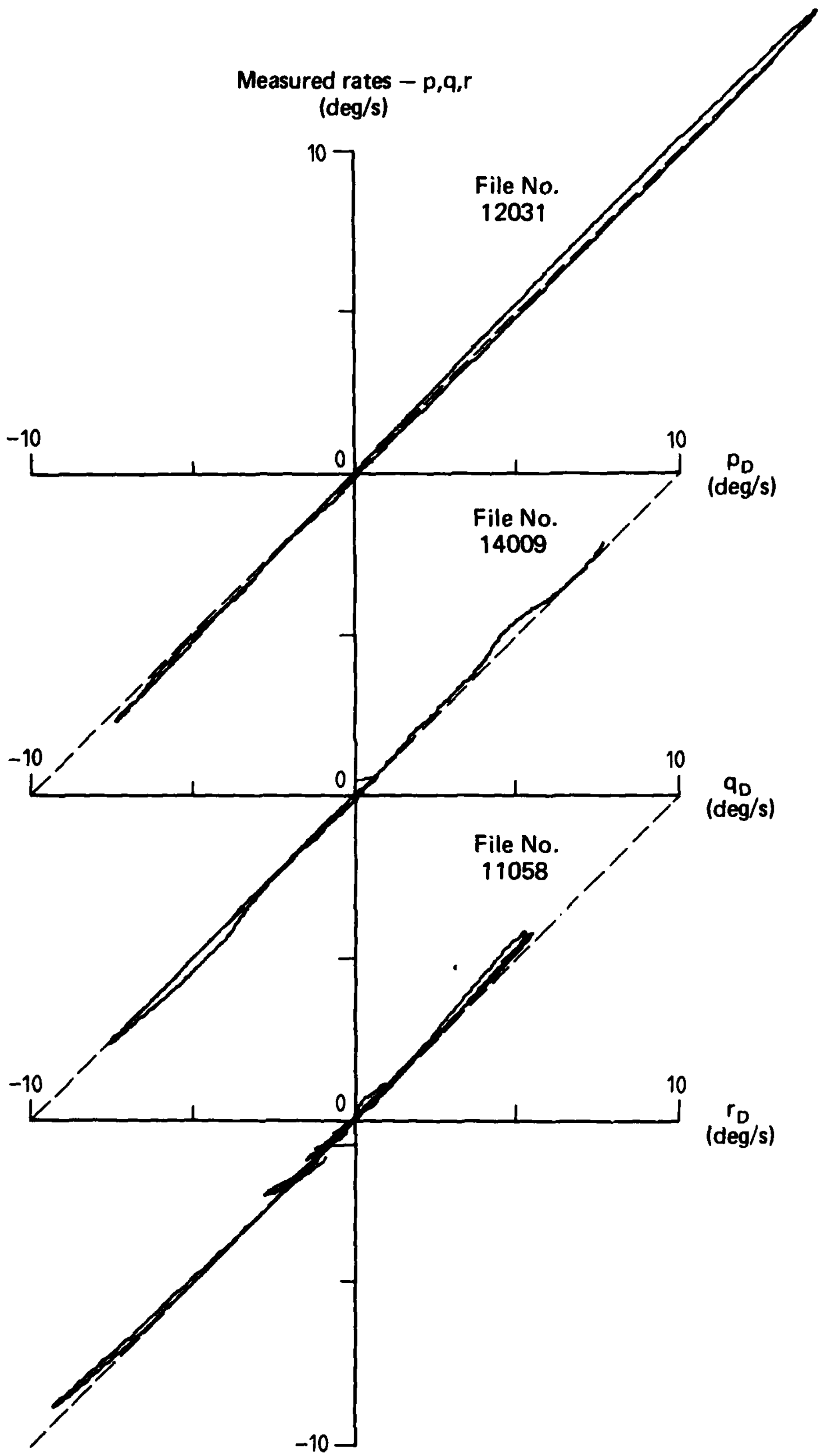


Fig. 6 As Fig. 4, but corresponding to results shown in Fig. 5

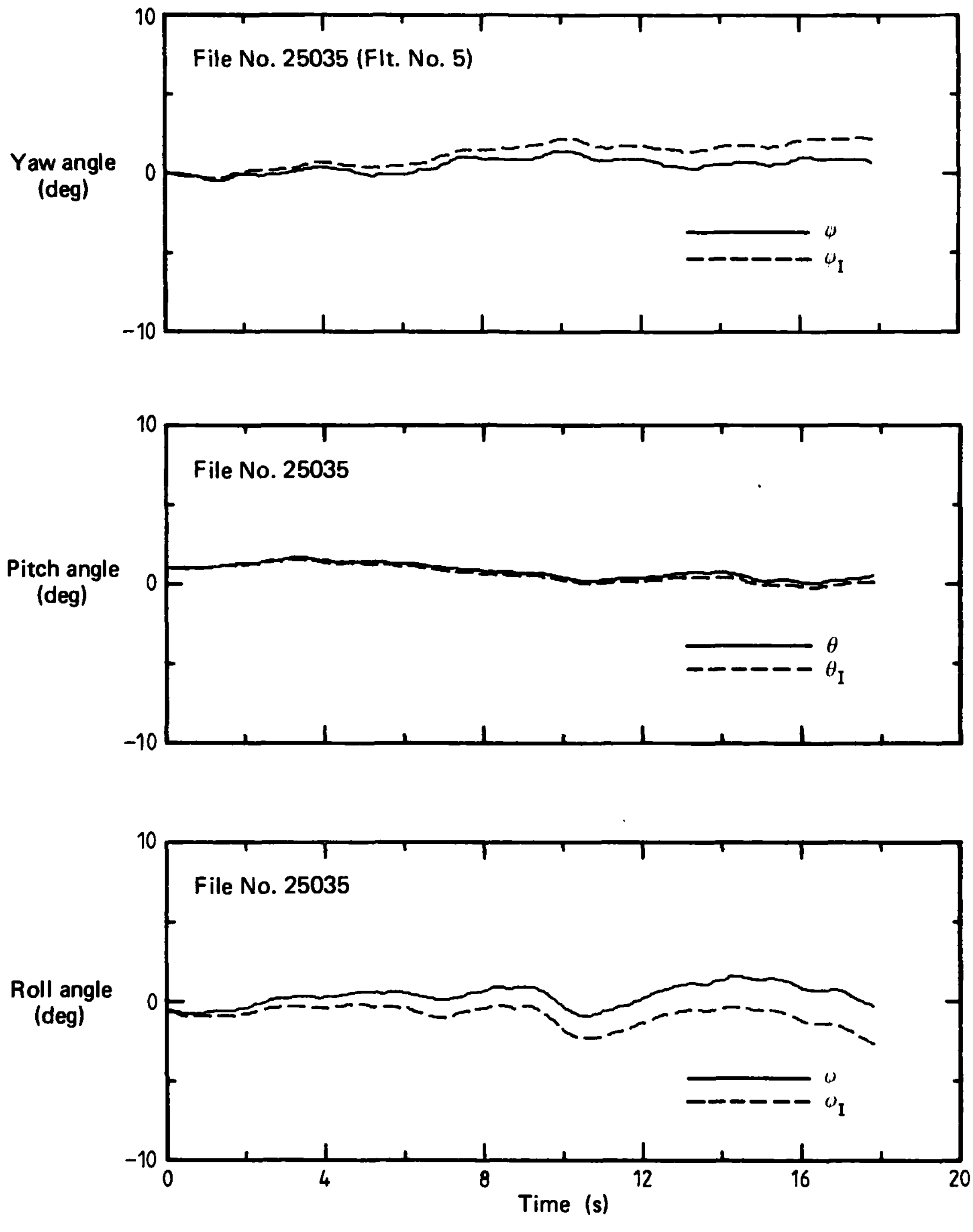


Fig. 7 Comparison between measured values of angular displacements and values derived by integration of angular velocities, for calibrations used in Fig. 5. Differences are attributed to integration of residual offset error in rate gyro calibrations

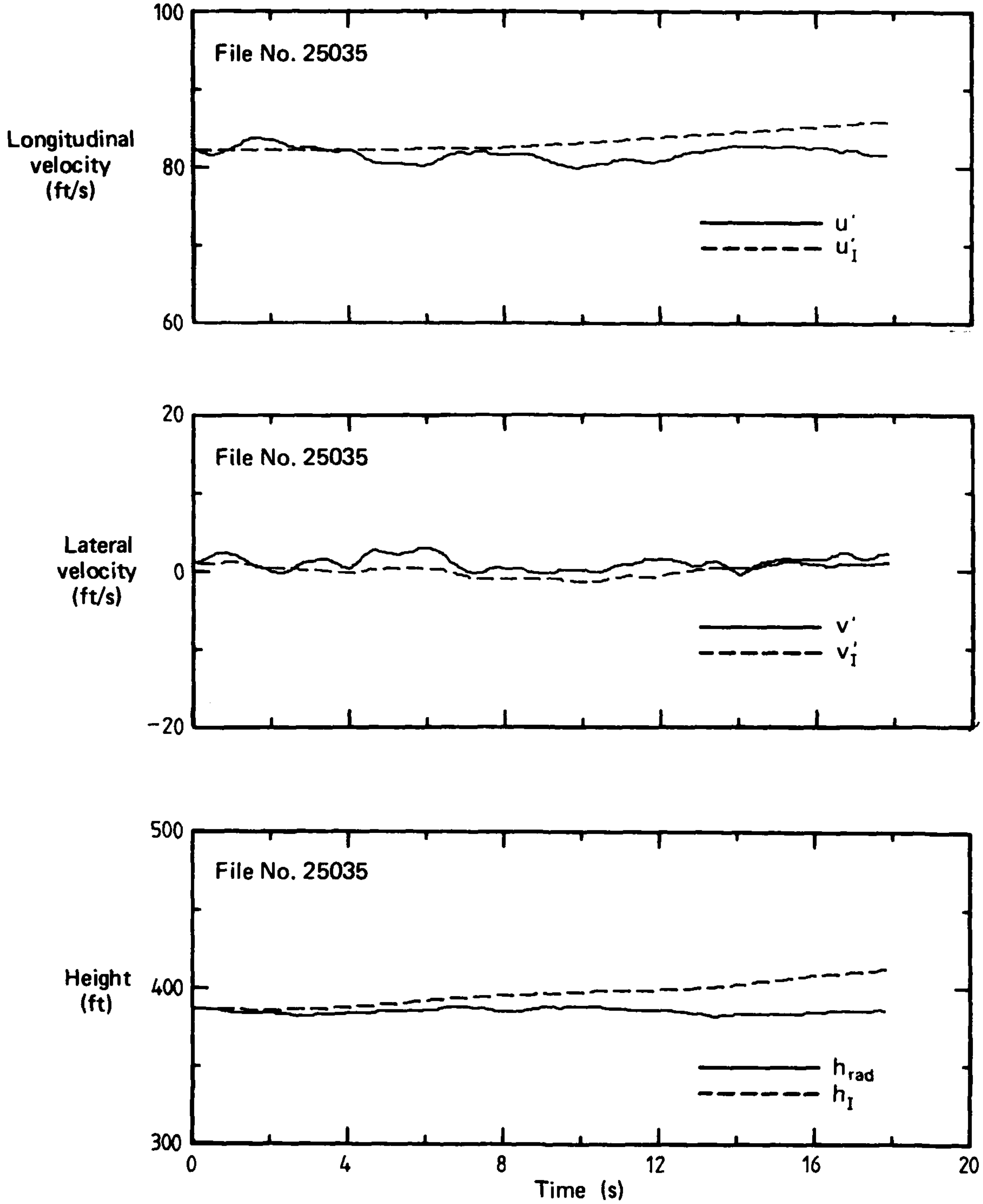


Fig. 8 Comparison between measured values of horizontal linear velocities and height and values derived by integration of linear accelerations, using initial estimates of accelerometer calibration offsets. Differences are attributed to integration of residual offset error in accelerometer calibrations

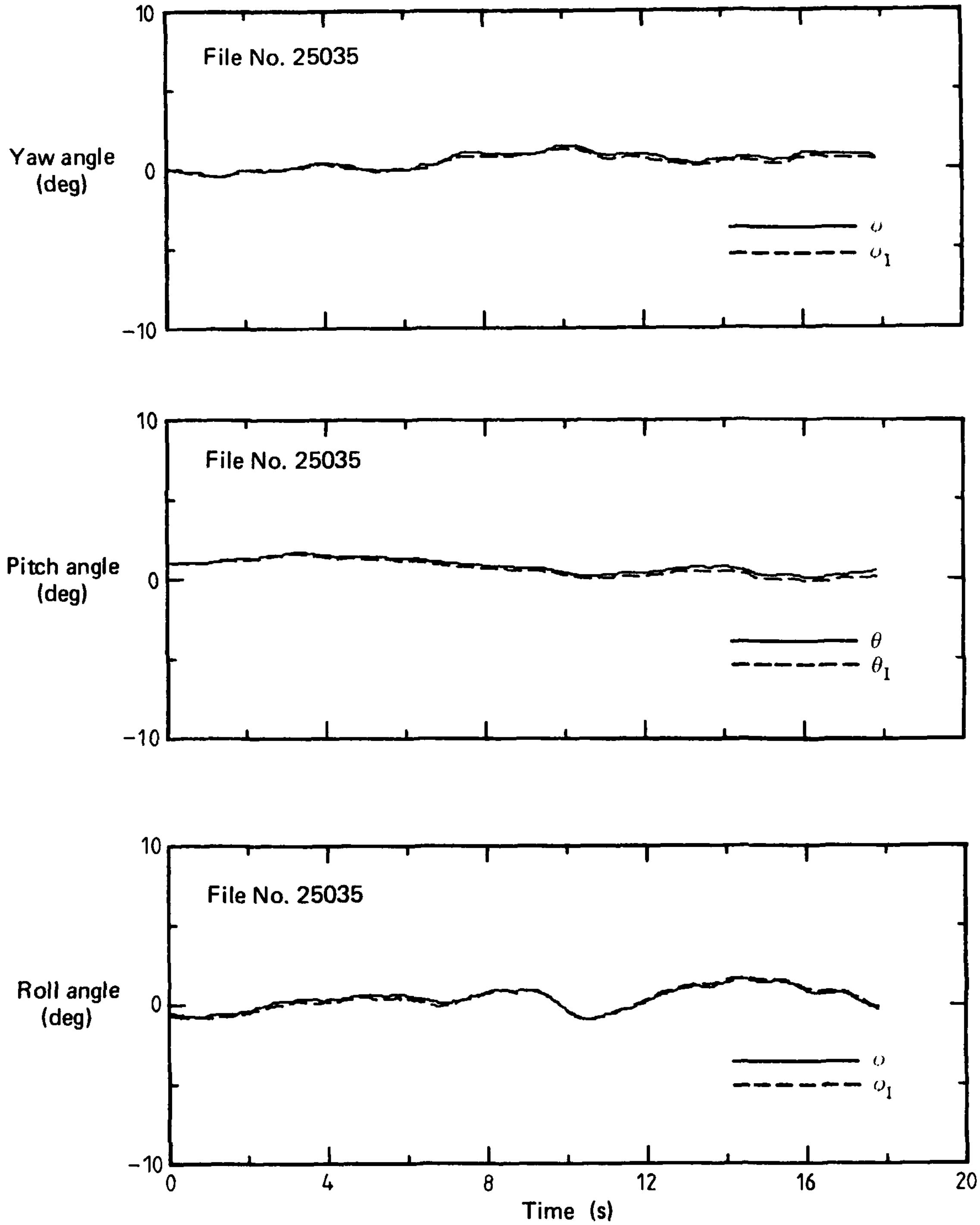


Fig. 9 As Fig. 7, but with rate gyro calibration offsets adjusted for residual error, based on averaging over a number of flight records

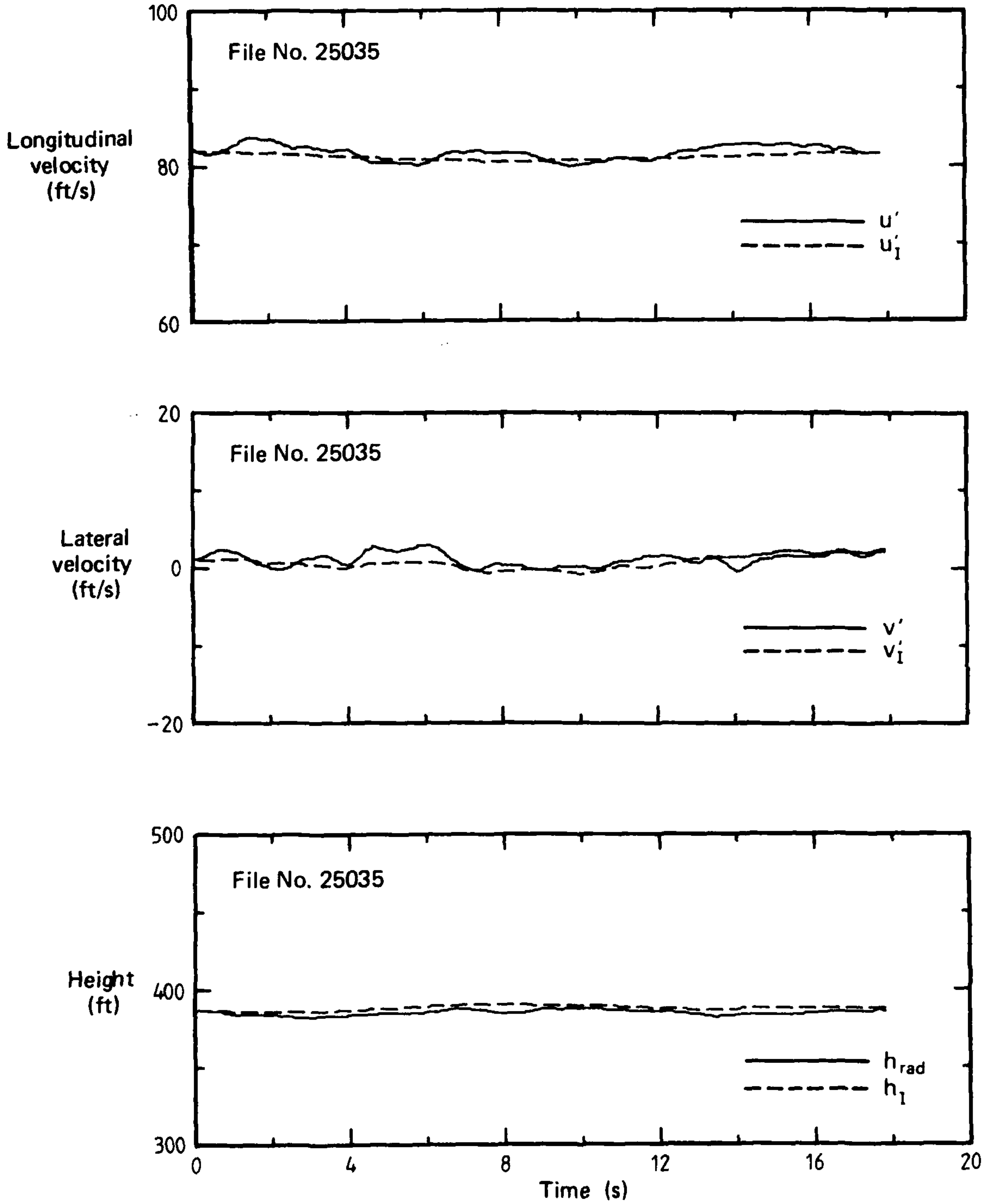


Fig. 10 As Fig. 8, but with accelerometer calibration offsets adjusted for residual error, based on averaging over a number of flight records

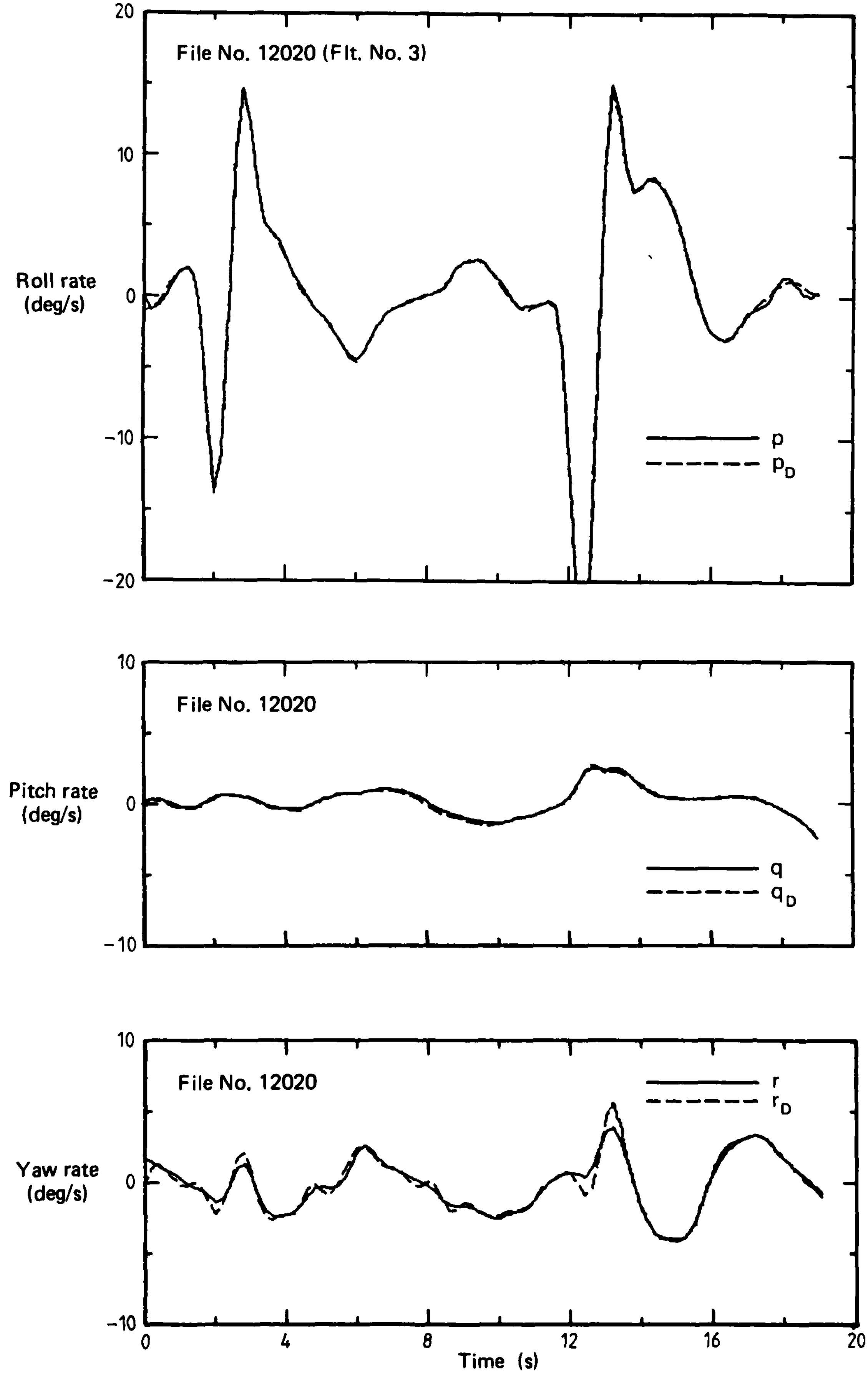


Fig. 11 Example of kinematic consistency checking of angular velocities using final calibrations

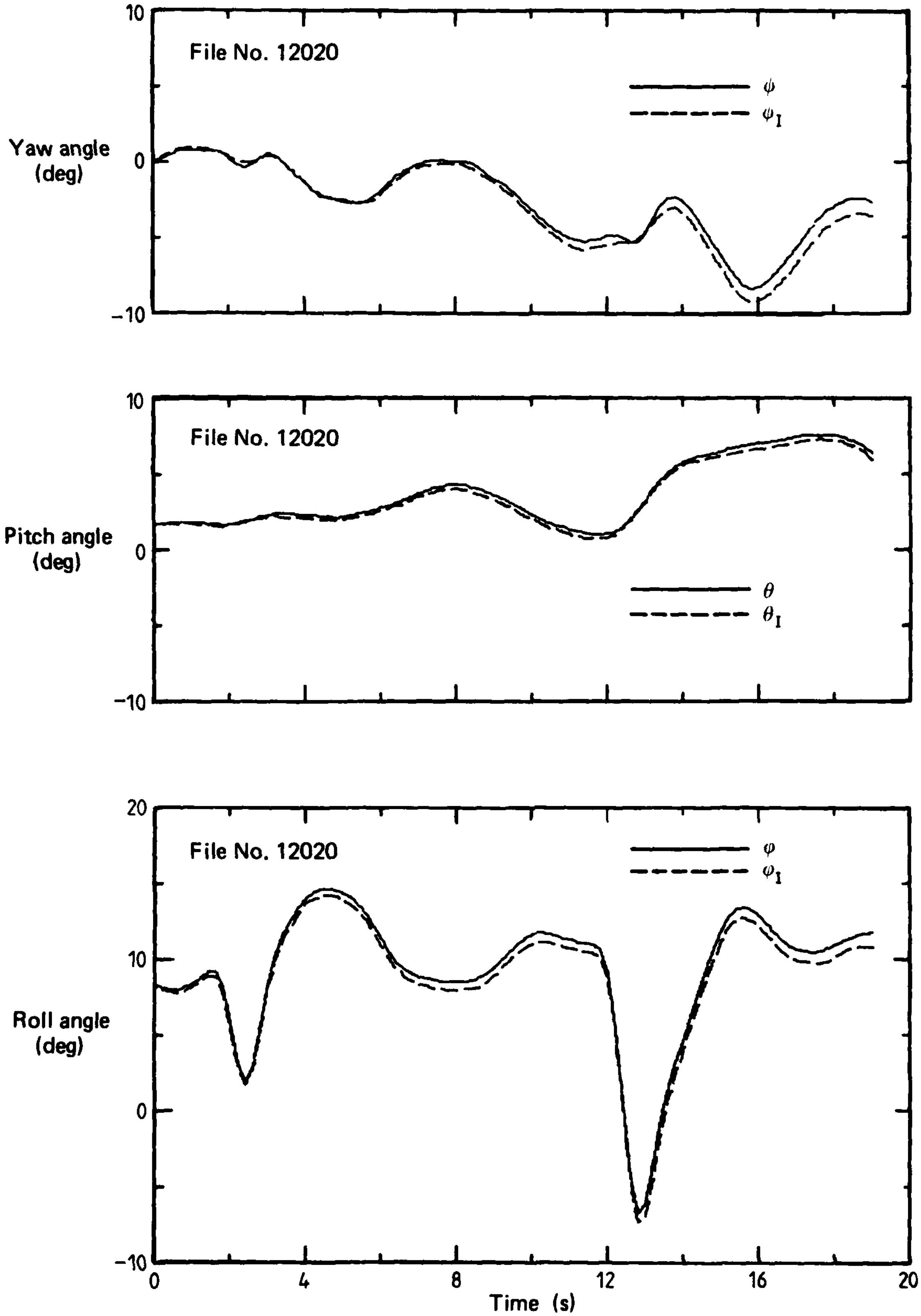


Fig. 12 As Fig. 11, but for angular displacements

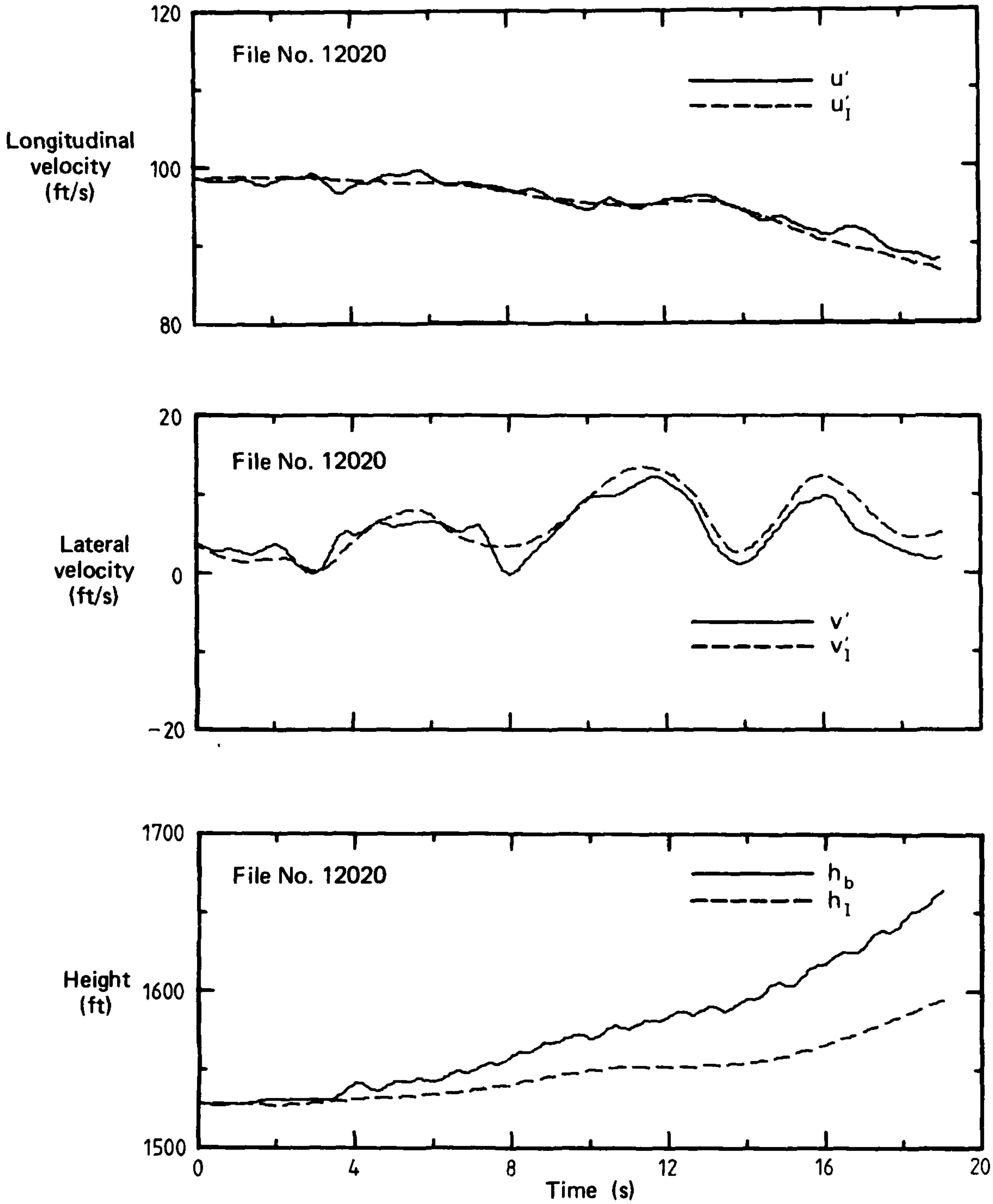


Fig. 13 As Fig. 11, but for horizontal linear velocities and height

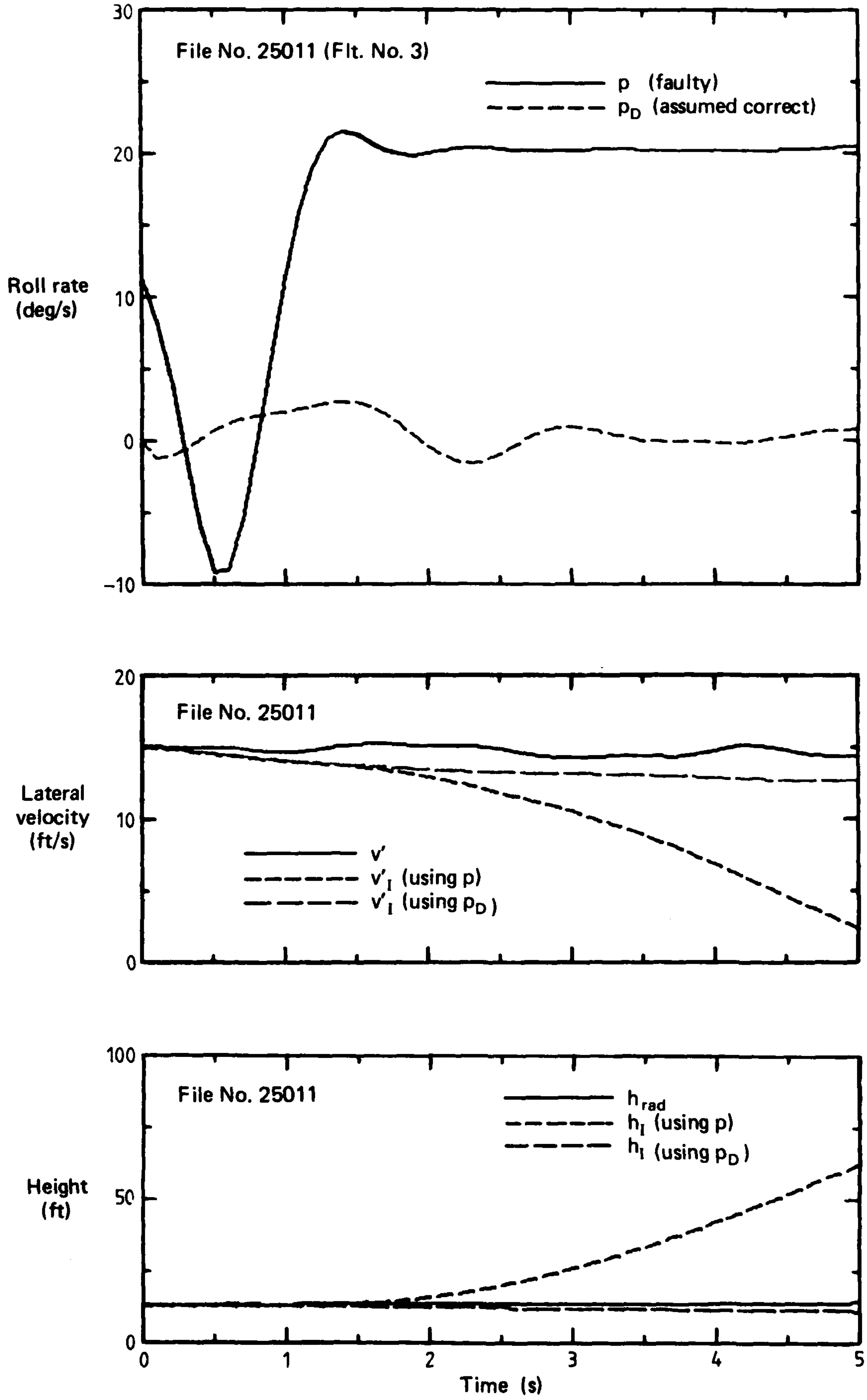


Fig. 14 Effect of replacement of faulty measured data (p) by derived data (p_D) in calculation of other quantities (v'_I and h_I)

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16. Abstract

A simplified approach to kinematic consistency checking applied to ARL Sea King helicopter flight trials data is given. Prompt implementation of the method has been possible, pending longer term development of systems identification techniques suitable for application in a general way to helicopter data. This has allowed the formation of a trials data bank with reasonable confidence in the kinematic quantities so that validation of the ARL Sea King mathematical model can continue. In the process adopted, measurements are first digitally filtered to remove noise. Alternative values of kinematic quantities are then derived from the smoothed measurements, using numerical differentiation or integration. For quantities obtained by integration,

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16. Abstract (Contd)

two separate iteration cycles are used, thus enabling the kinematic equations to be integrated independently by "separation of variables" using the trapezoidal formula. Uncertainties in some calibration constants are resolved using differences between measured and derived kinematic quantities. A procedure for the replacement of suspect angular measurements by derived values in the calculation of other dependent quantities is described and demonstrated.

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